NORMA – A NOrmal conducting Racetrack/Ring Medical Accelerator

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Outline

- Outline the motivation for a normal conducting scaling FFAG for medical applications
- Present the method we used to optimise an FFAG design in PyZgoubi
- Show progress on designing an FFAG
  - Ring
  - Racetrack

Radiotherapy Statistics for UK

- 'Radiotherapy Services in England 2012', DoH
  - 130,000 treatments, most common age around 60 yrs
  - 2.5 million attendances
  - More than half of attendances are breast/prostate

- X-rays
  - 265 linacs in clinical use
  - Almost all machines IMRT-enabled, 50% IGRT (Image-Guided)
  - Each machine does >7000 'attendances'
  - 147 more linacs required due to increasing demand

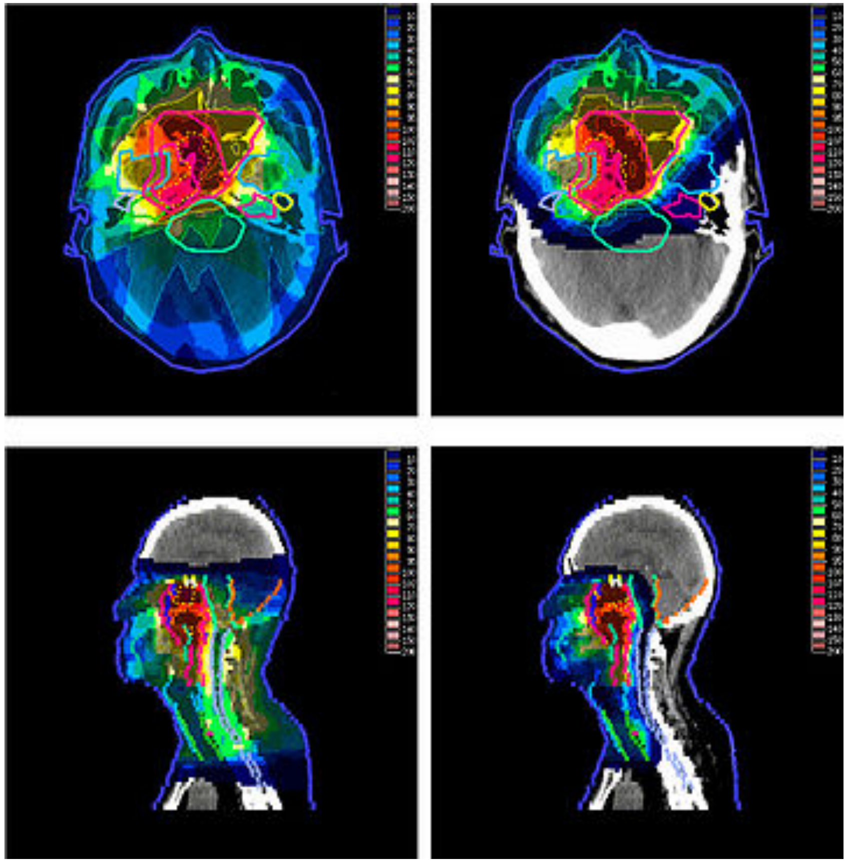
- Protons
  - 1 centre (Clatterbridge) operating, c.62 MeV (ocular treatments)
  - 2 centres (UCLH and Manchester) in contract, due 2018
  - Perhaps a 3rd private centre in discussion (Oxford)

- Cancer care
  - 40% curative treatments utilise radiotherapy
  - 16% cured by radiotherapy alone

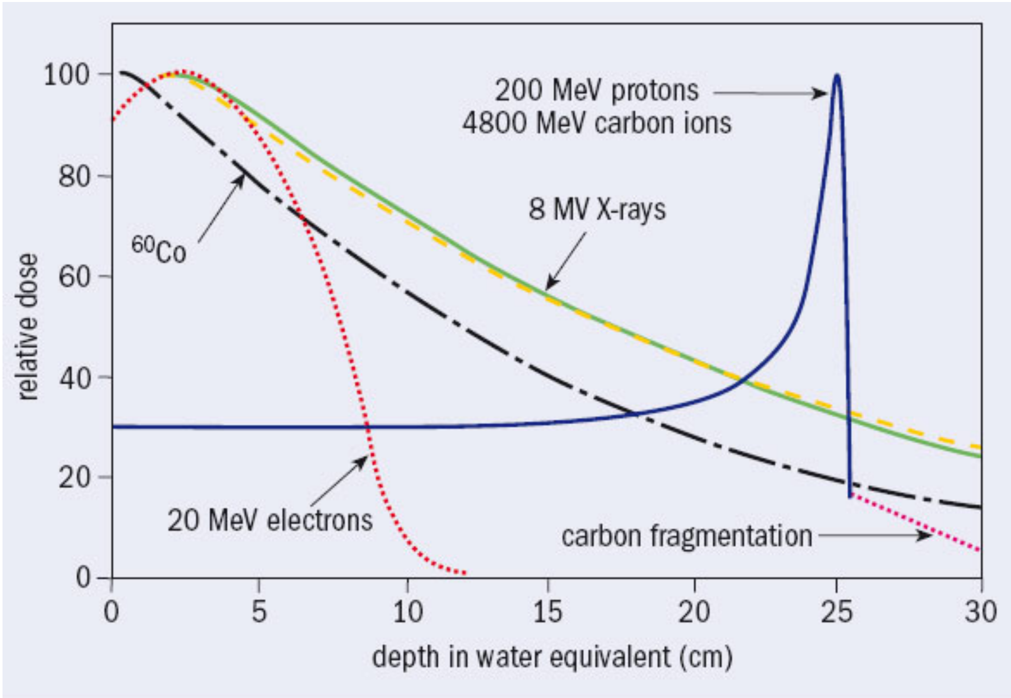
Reference: H. Owen, Int. J. Mod. Phys. Oct. 2013

Protons vs X-Rays

Reference: H. Owen, Int. J. Mod. Phys. Oct. 2013



IMRT (Intensely Modulated RadioTherapy):
X-rays + IMRT provide sufficient conformality of dose to tumour volume but irradiate other depths



Proton therapy offers Bragg peak and thereby improve avoidance of critical nearby structures cf. conventional x-ray therapy

Most important is the lack of *distal* dose downstream of the Bragg peak

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

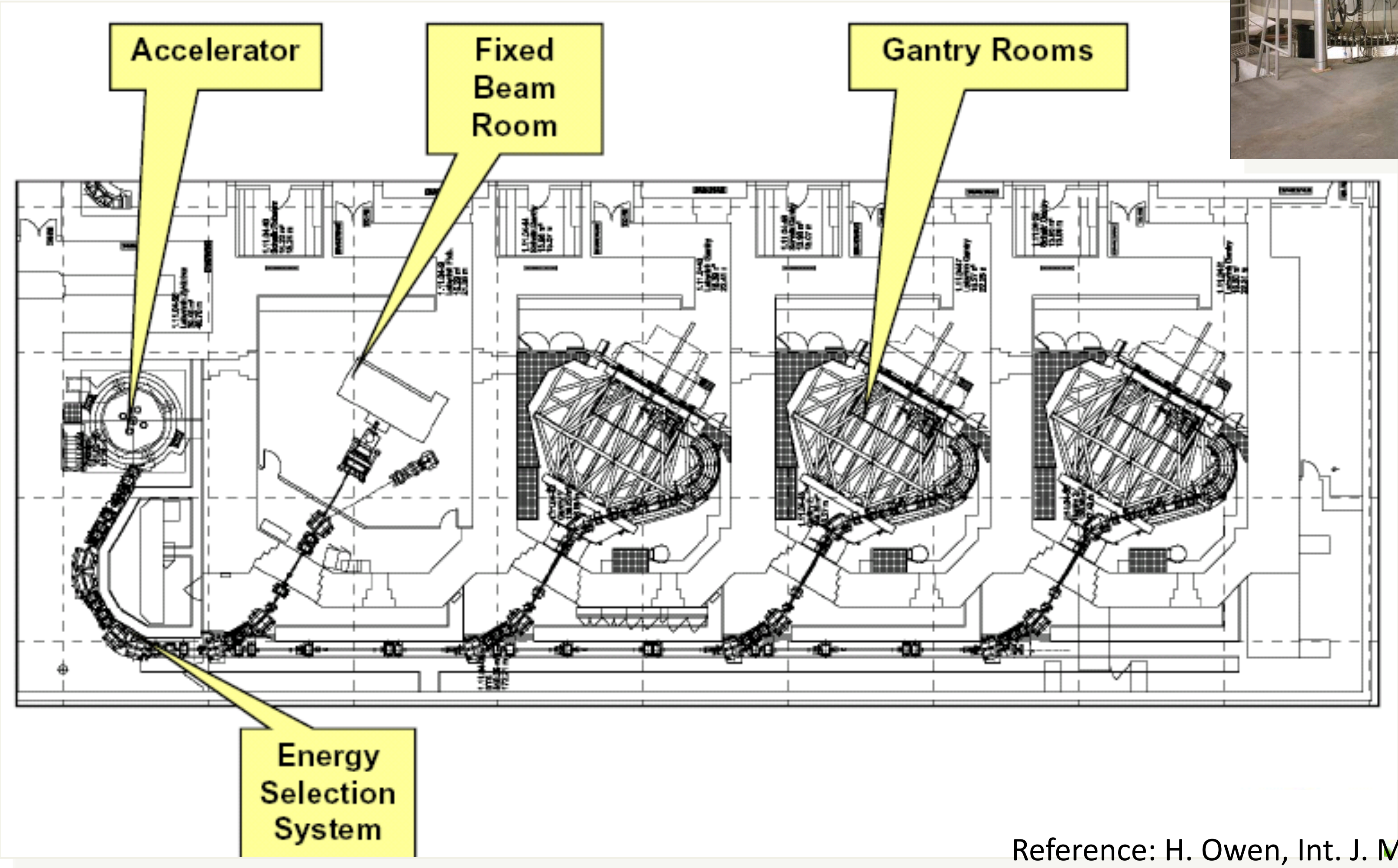
Clinical Specification

- Adult treatments:
  - Energy range c.70 to c.230 MeV (lower energies beneficial)
  - 1 Gy per minute into 1 litre treatment volume = 100 gigaprotons in 1 minute
  - i.e. around 0.1 nA effective proton current at the patient
  - 1 kHz pulse rate ideal (allows repainting/dose control)
  - Energy steps 5 MeV or less
  - Small enough to fit onto hospital site easily?
- Adult imaging:
  - Maximum energy c.350 MeV (for good energy resolution in pCT scanner)
  - Around 0.1 gigaprotons for imaging, in a few minutes (gantry rotates)
- A number of groups are working towards pCT detectors, but there is as yet no suitable proton source
  - This is the motivation for NORMA
- UK presently constructing 2 proton therapy centres (UCLH London and Christie Manchester)
  - 750 patients per year, per site
  - Around 2/3 adult treatments, 1/3 children
  - All complex cases needing superior dose control, many of which will benefit from improved imaging

Reference: H. Owen, Int. J. Mod. Phys. Oct. 2013

Example of clinical centre (cyclotron)

It's got to offer advantages over this! ->

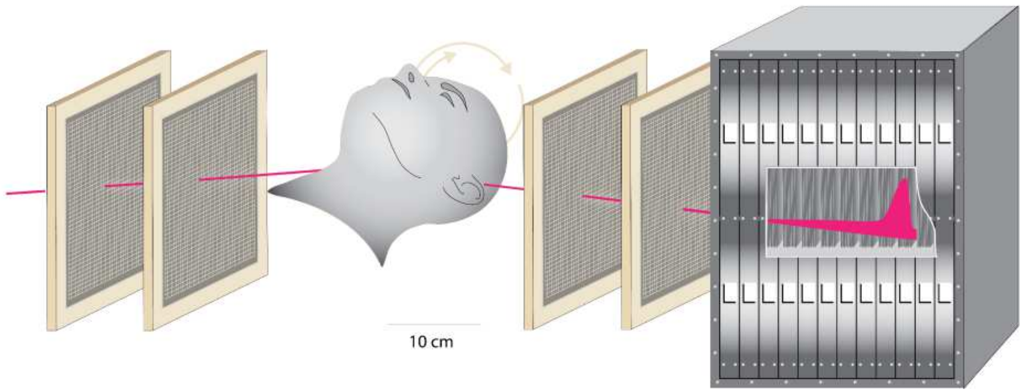


Reference: H. Owen, Int. J. Mod. Phys. Oct. 2013

Motivation

- Commercial (and other) technologies already exist for effective proton therapy:
  - Cyclotron; limited to c.250 MeV, high dose rate but limited speed of energy variation
  - Synchrotron; simpler accelerator, lower dose rate, more complex energy variation
  - Linac/cyclinac; potential for rapid energy variation, but higher losses and not yet demonstrated
  - Other technologies (laser plasma, dielectric etc.) less mature
- Need for improved imaging to reduce tumour treatment margin c.5->3mm
  - Proton computed tomography (pCT) is one favoured option, but needs a suitable proton source
  - c.350 MeV protons required for adult tomography

Proton tomography tracks individual protons' incoming/exit trajectories + measures energy loss in patient by measuring residual energy in calorimeter. A large number of tracks (c. 10-100M) allows density of patient to be reconstructed tomographically to reasonable resolution (<3 mm)



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FFAGs could be a good choice

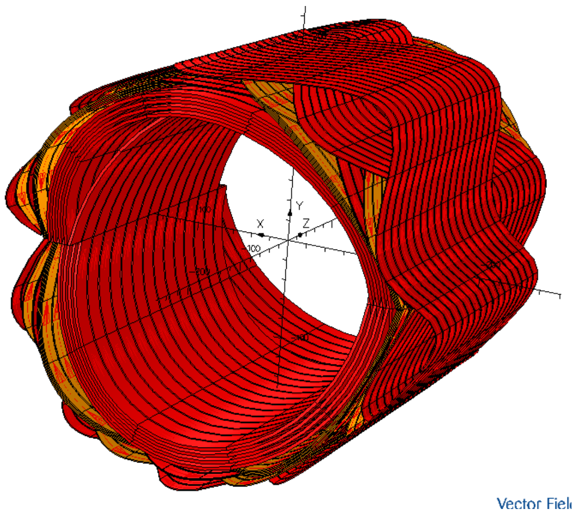
- Fixed-field normal conducting magnets. May loose compactness but gain some simplicity in magnet design/price/maintenance
- Can attain 350 MeV.
- High repetition rate – can synchronise with patient breathing and deliver almost constant dose.
- Energy can be changed rapidly and energy scanning can meet clinical requirements and make more accurate treatment.
- No need for degraders. Less shielding.
- If we have an FFAG gantry then we don't need energy selectors and several treatment rooms – reduced cost.

What we plan to do

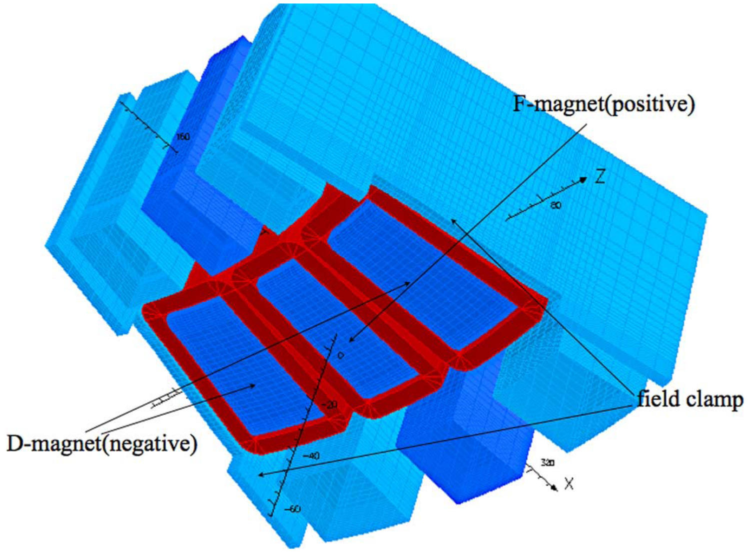
- Design a normal conducting, proton, **scaling FFAG** ring and racetrack variation for medical applications.
- Energy range of **30 – 350 MeV** would enable good energy range for tumor treatment and also useful diagnostic abilities - Proton Computed Tomography (PCT).
- **Normal conducting**, fixed-field magnets may be simpler and cheaper to construct compared to other accelerator proposals.
- Following from previous work by Machida (PRL 103, 164801 (2009)) and the PAMELA collaboration (PRST-AB 16, 030101 (2013)) – high field index so smaller orbit excursion.
- Exploration of a **racetrack** design may utilise compact arc sections in conjunction with longer, magnet-free drift sections for easier injection/ extraction and RF modules.

Normal conducting (NC) magnets

- Super-conducting is generally more expensive than NC.
- Scaling field could be achieved with pole-face shaping rather than individual coil windings for each multipole.
- Several examples of FFAGs have been built which use NC, scaling FFAG type magnets (ERIT, KURRI ADSR FFAG, PoP FFAG).



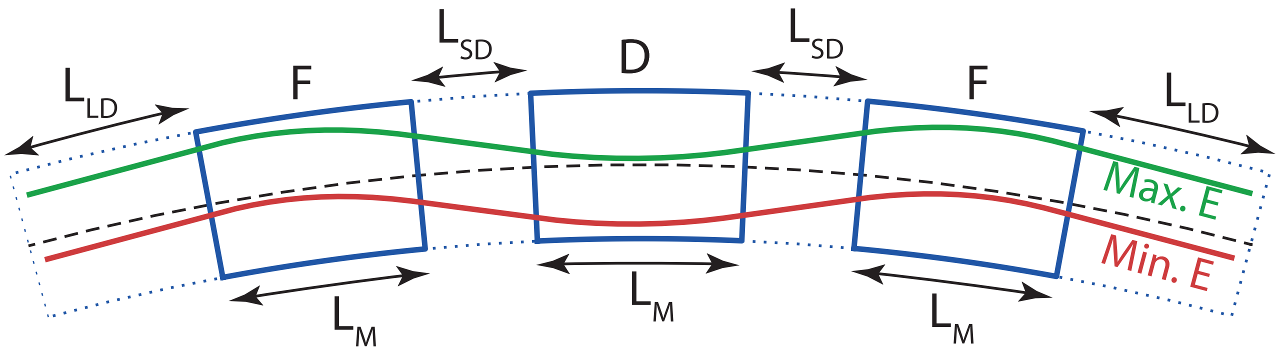
H. Witte and PAMELA collaboration



ERIT collaboration

NORMA - Ring

- Started with basic PAMELA parameters:
  - 12 FDF triplet cells
  - Cell component lengths
  - Working point (8.64,3.48)
- Changed to scaling-FFAG, radial-sector magnets, 350 MeV.
- Changed max magnetic field form ~4T to 1.8T and calculated the rigidity of the 350 MeV orbit -> used this as the radius.
- This yields a ring with a radius of 17.5m (PAMELA 6.25m) – **impractical**.

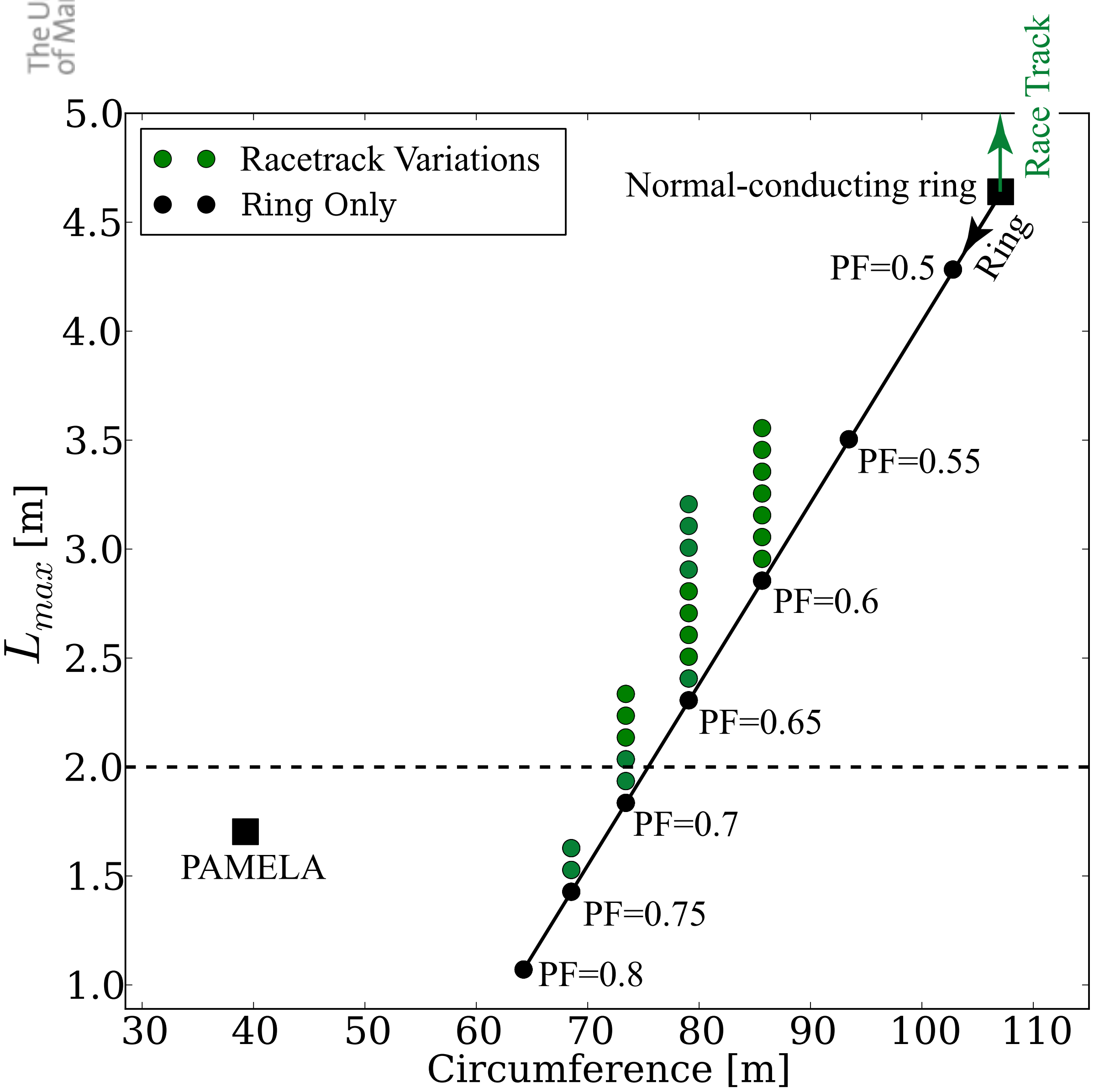


FDF Triplet

NORMA - Ring

- Want to reduce lattice size, minimise L_{SD}, L_{LD} and L_M
- Developed routines in PyZgoubi to optimise magnetic parameters to a specific working point for different lattice geometry
- B_{0F}, B_{0D} and the field index *k* were adjusted by the optimisation routine to meet the working point requirement
- Routine: minimised a penalty function created from several criteria:
  - Stability ($|Tr(M)| < 2$) for all energies
  - **Distance from given working point**
  - Distance of 350 MeV closed orbit form r_0 (defined by 350 MeV orbit rigidity)
- Can use anything in the optimisation routine, e.g. optics values – very flexible. Can be used for matching.

NORMA - Ring

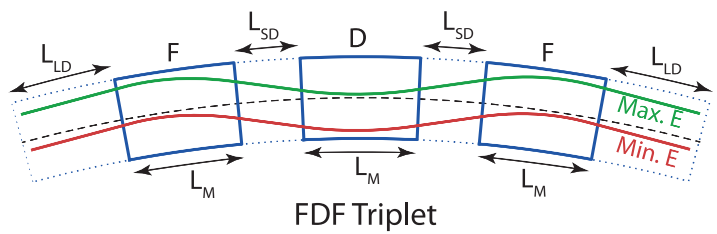


Working point fixed initially to (8.64,3.48) in horizontal and vertical ring tune.

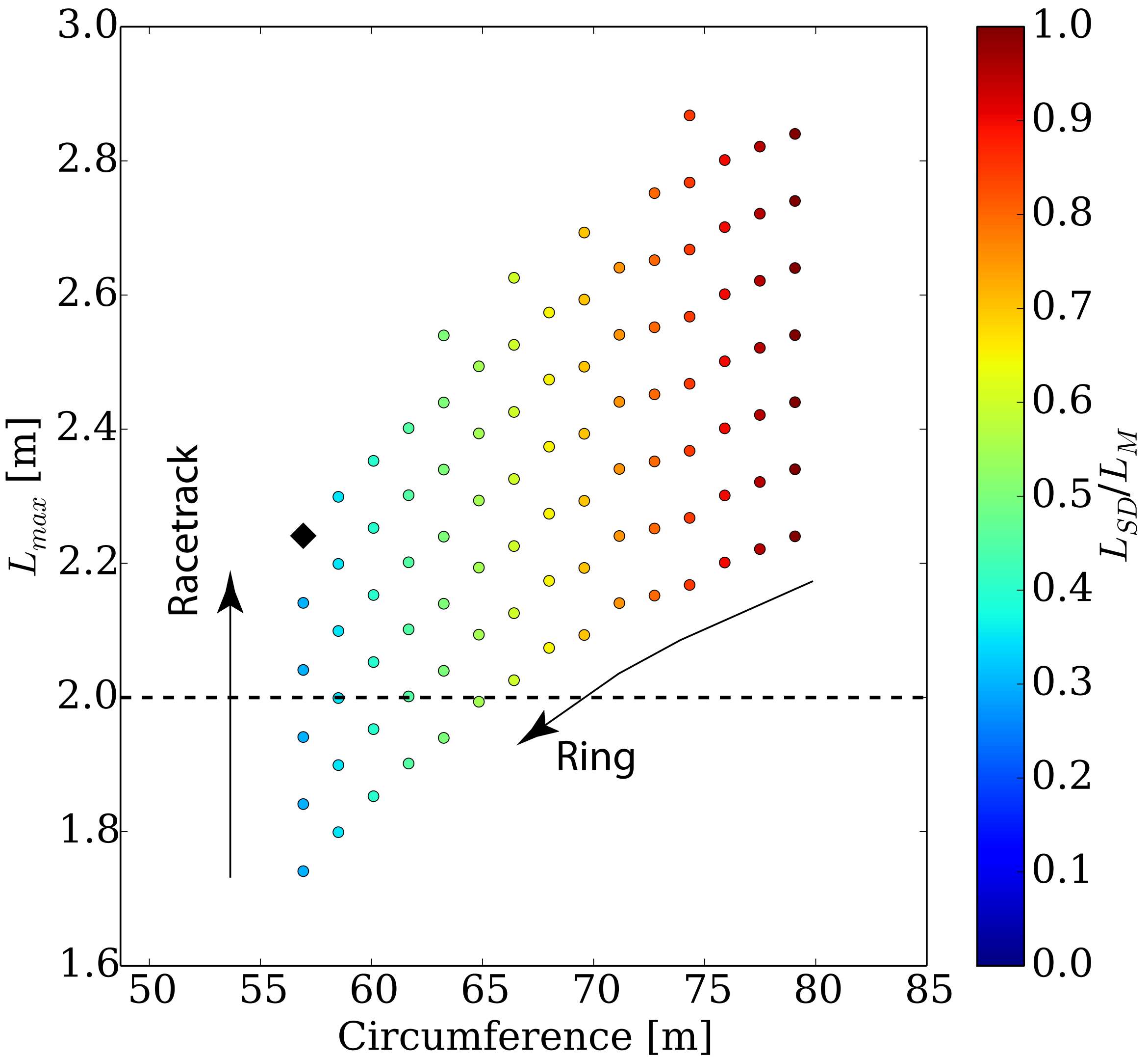
Packing factor increased to reduce size.

Max straight length L_{max} = 2m preliminarily chosen.

0.65 chosen for further study as all lattices have L_{max} > 2m.



NORMA - Ring

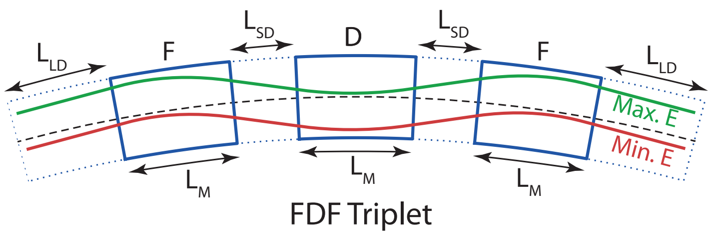


Length of L_{SD} reduced.

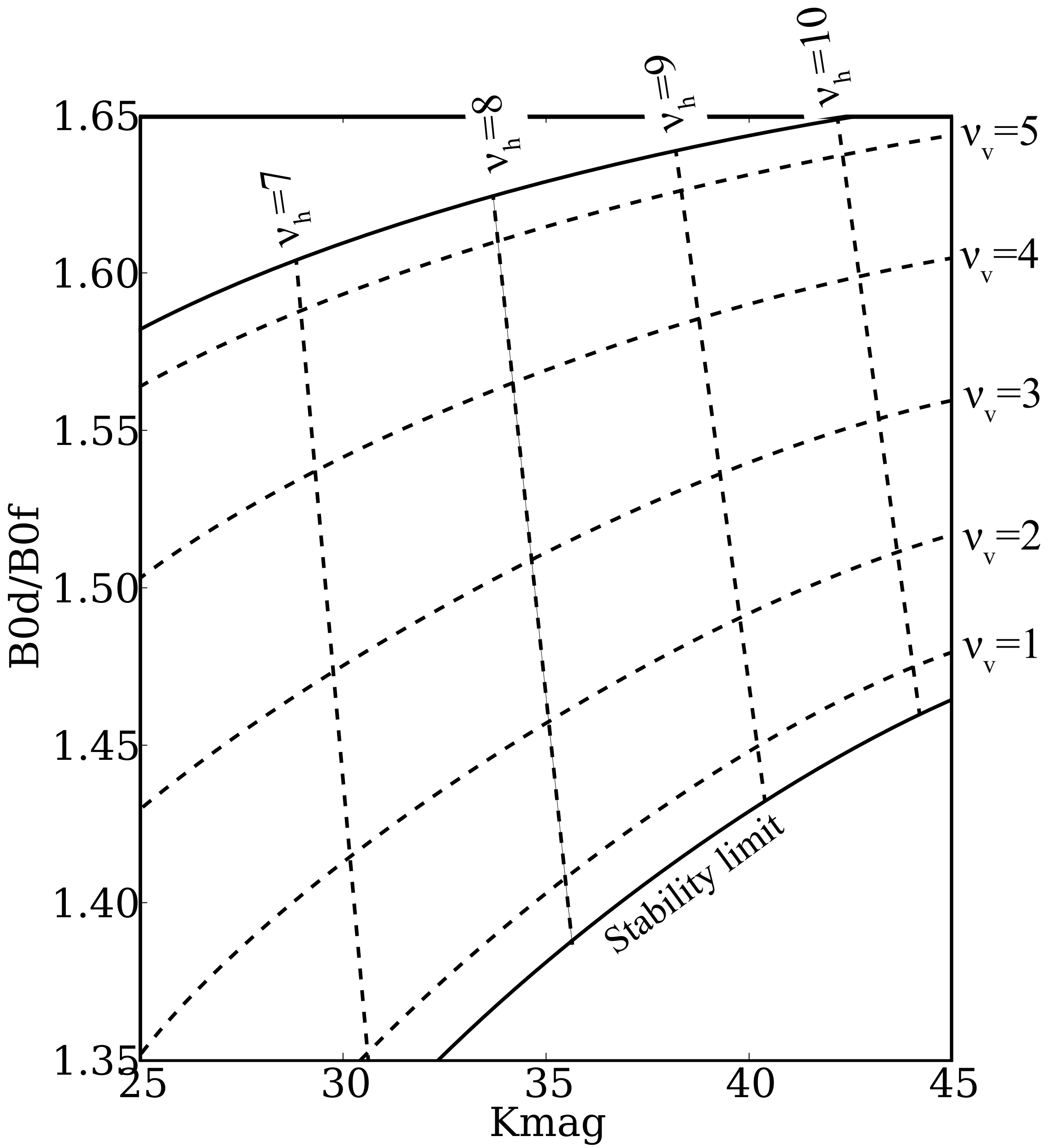
Using $L_{SD}/L_M = 0.3$ we are able to make the smallest racetrack with $L_{max} > 2$m.

Circumference of smallest machine is 56.9 m.

Selected for further study…



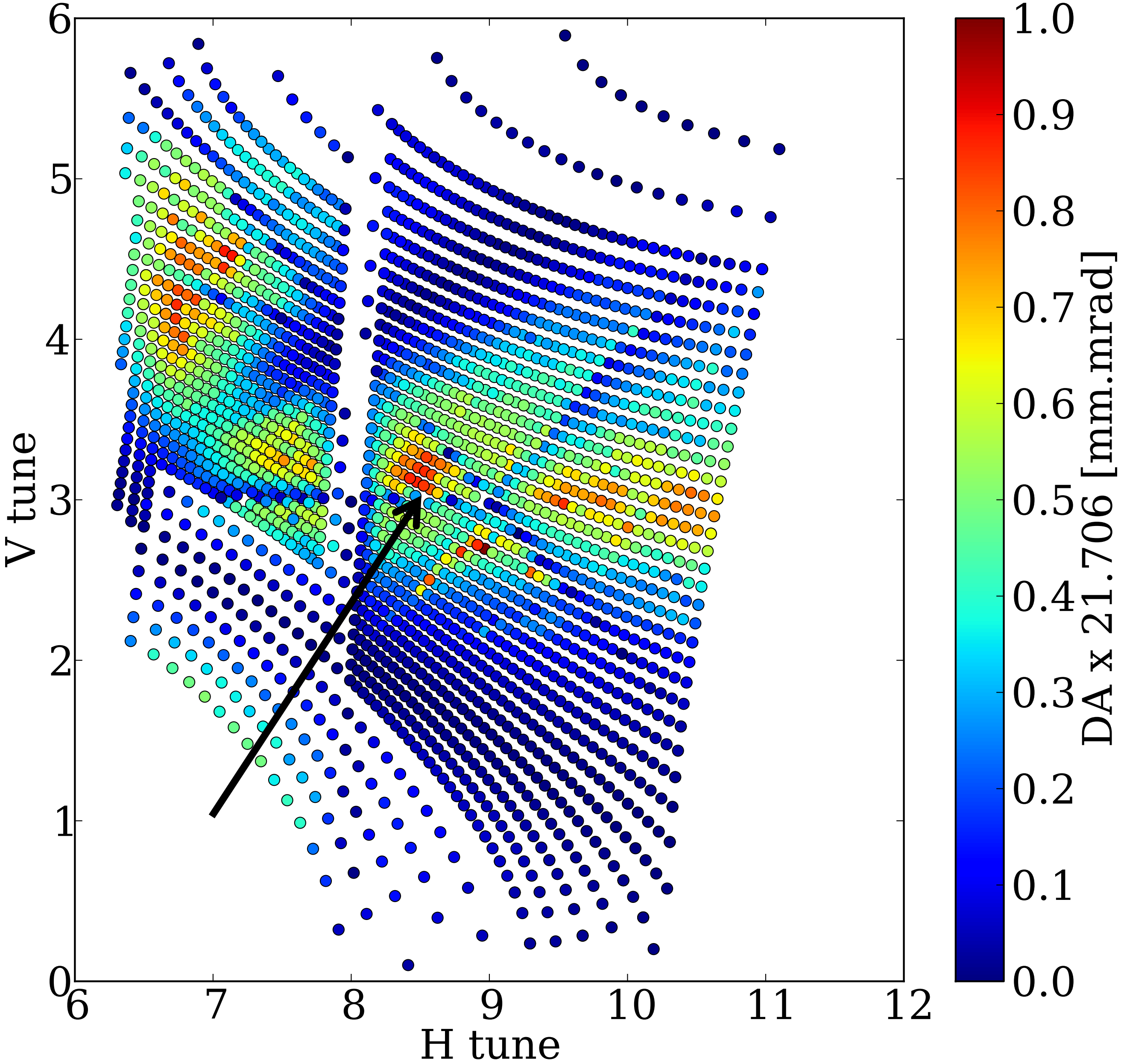
NORMA - Ring



Smallest stable ring found by the PyZgoubi routine was investigated.

Stability diagram with ring integer tunes indicated.

NORMA - Ring



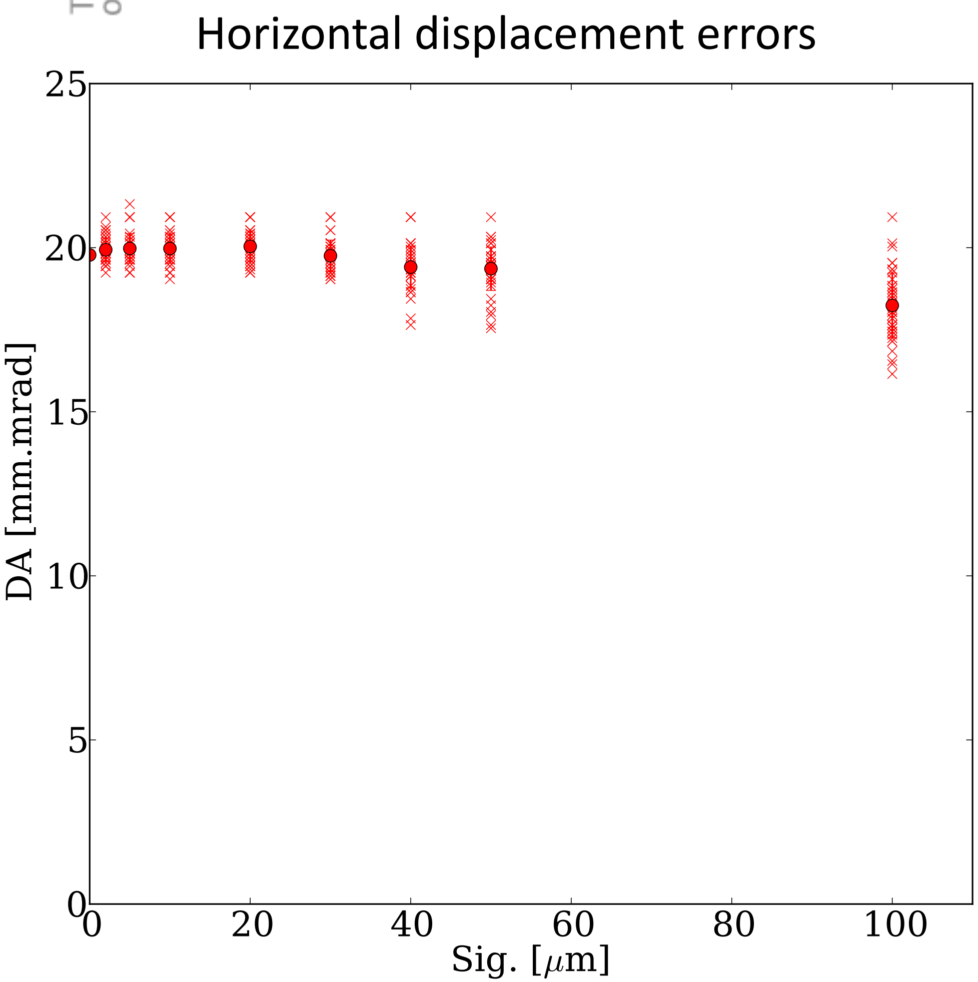
DA: rigorous measurement (see Sam Tygier's talk).

DA in the tune space normalised to the max value of 21.7 mm.mrad.

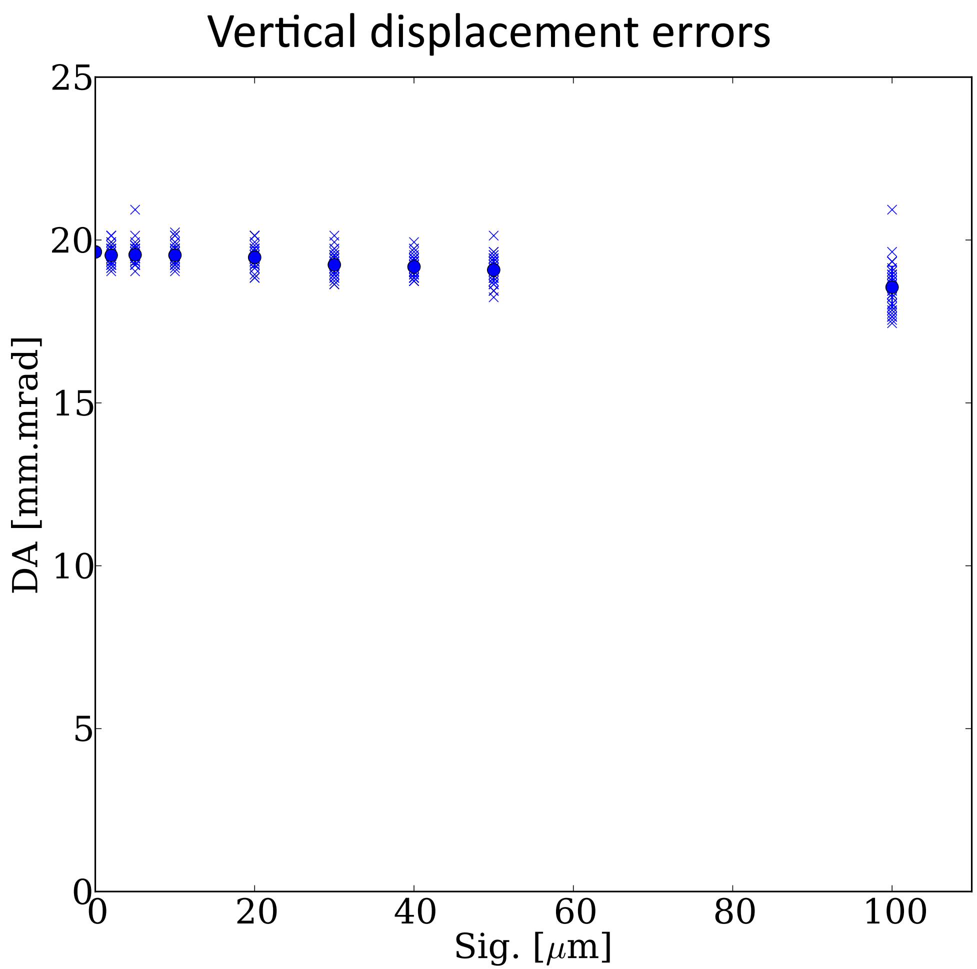
The region indicated has the highest DA sector for the smallest orbit range.

DA is too low in this region < 20 mm.mrad.

NORMA - Ring

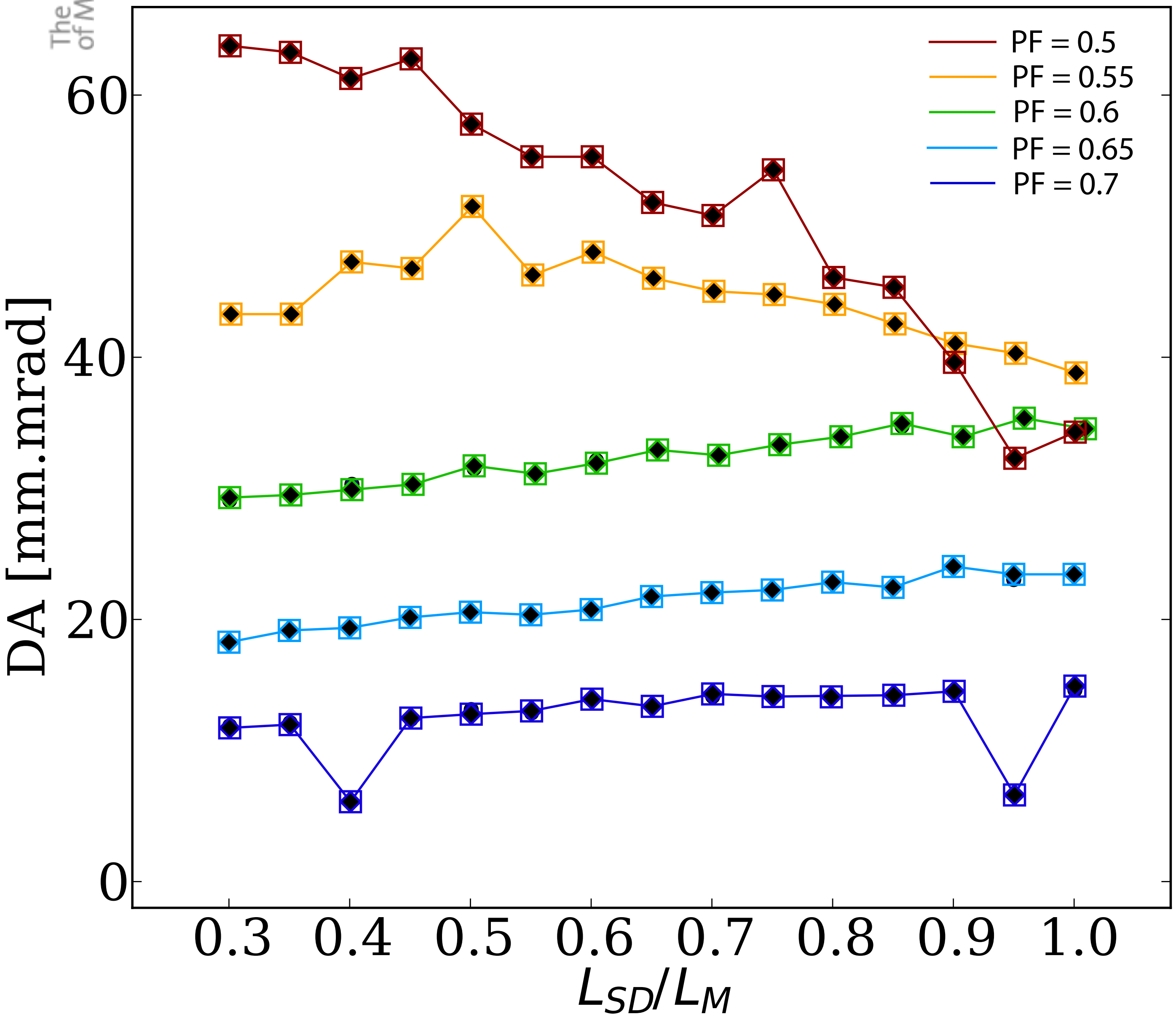


Horizontal displacement errors
DA [mm.mrad]
Sig. [μm]
0
5
10
15
20
25
0
20
40
60
80
100



Vertical displacement errors
DA [mm.mrad]
Sig. [μm]
0
5
10
15
20
25
0
20
40
60
80
100

NORMA - Ring



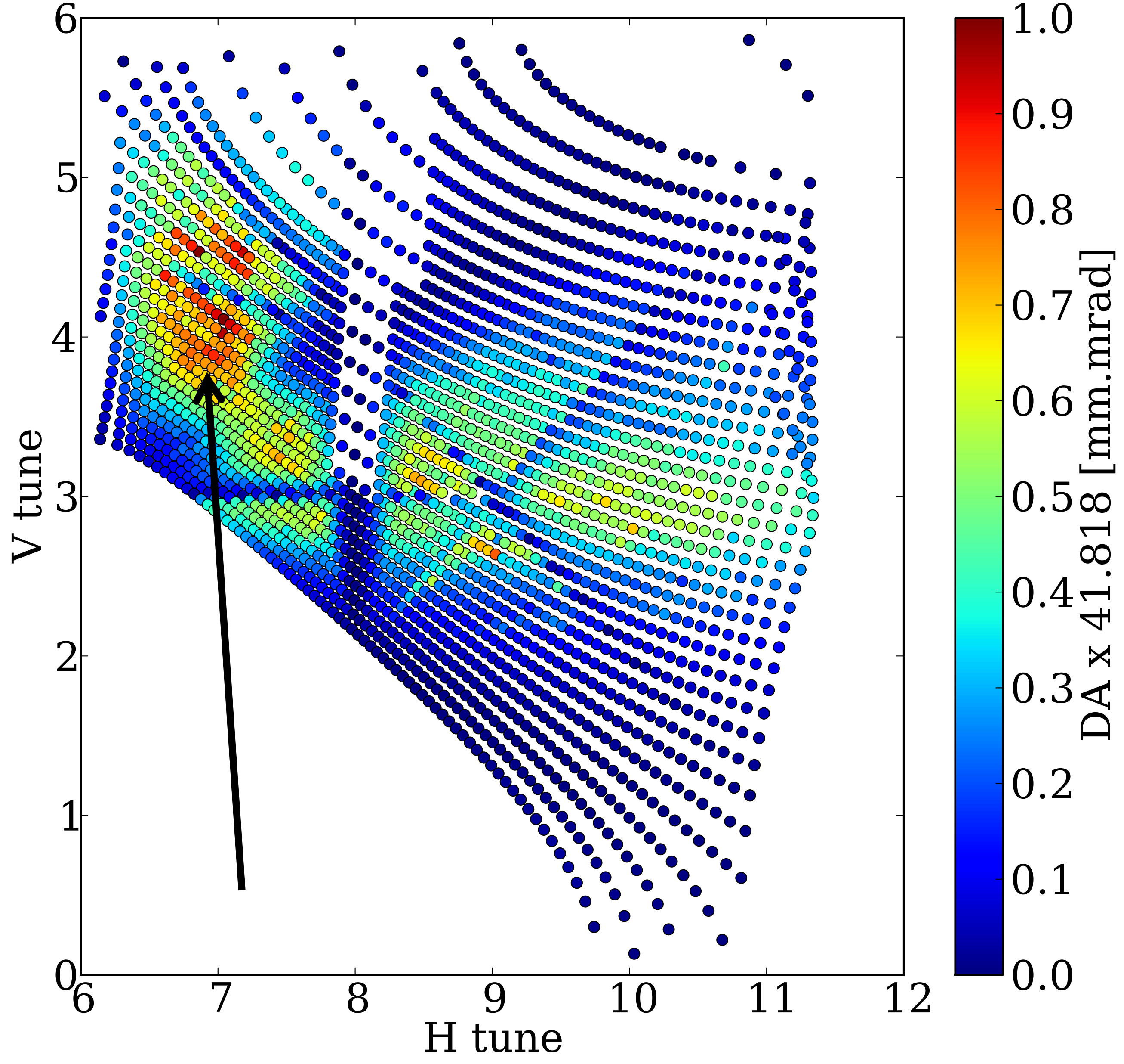
Keeping the working point fixed (8.64, 3.48) the DA was calculated for the geometric parameter scans.

We calculated PAMELA's DA to be around 30 - 40 mm.mrad.

Relax packing factor and circumference to gain DA.

Packing factor 0.6 allows DA > 30 at this working point.

NORMA - Ring



DA in the tune space for packing factor of 0.6.

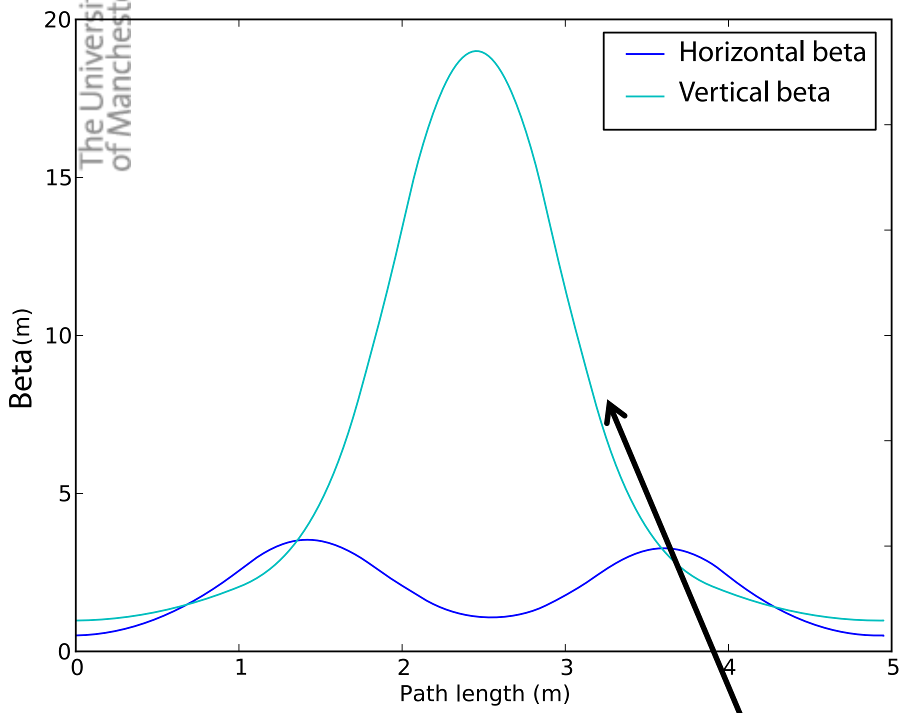
However the DA increases if we change the working point from (8.64, 3.48).

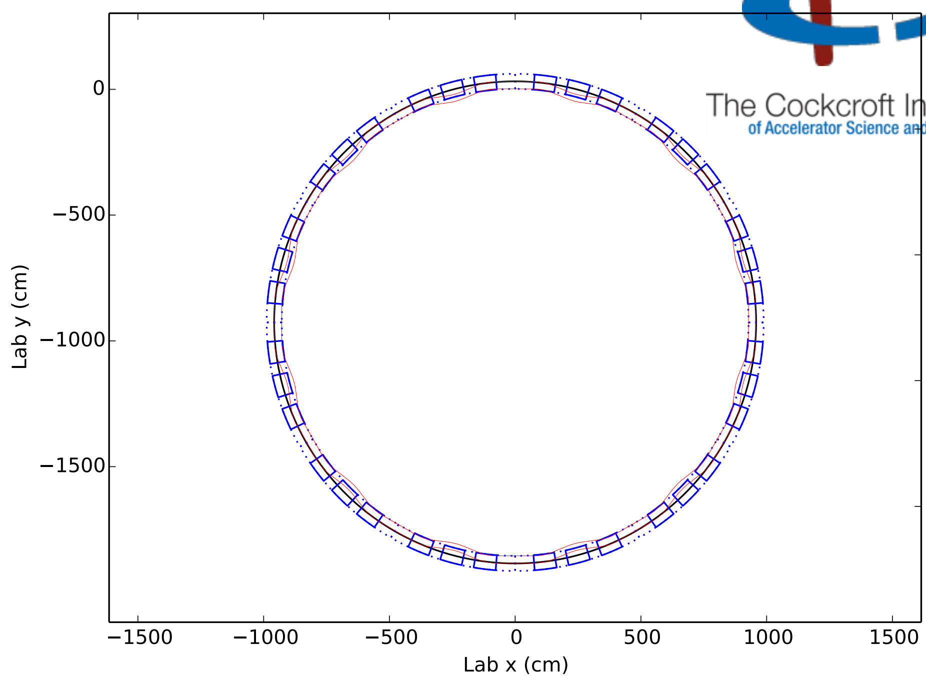
Working point lowered to (6.95,3.90) with a slightly larger orbit excursion but 2x DA.

Radius is now ~ 61 m.

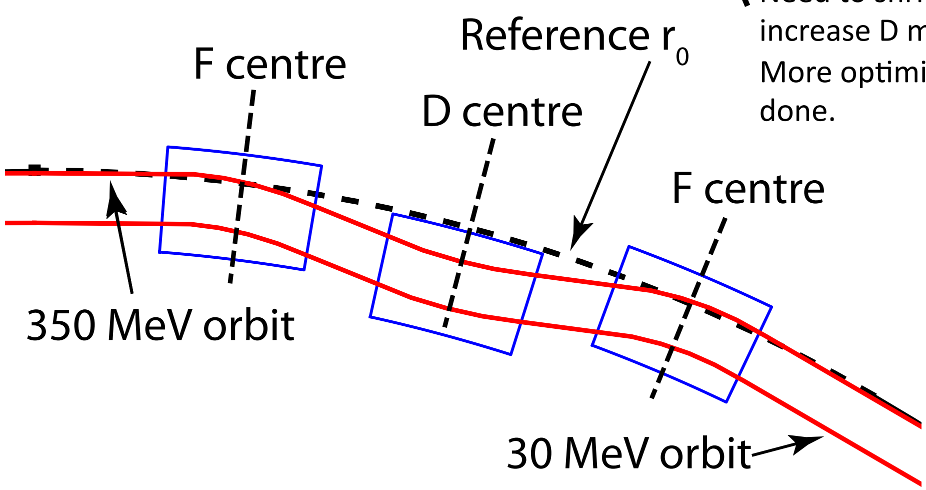
This lattice selected for second iteration.

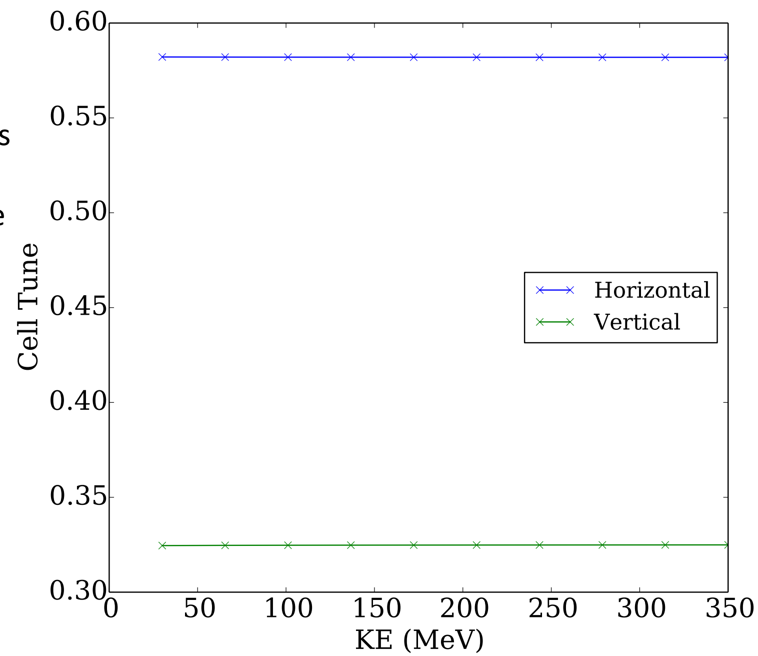
NORMA - Ring





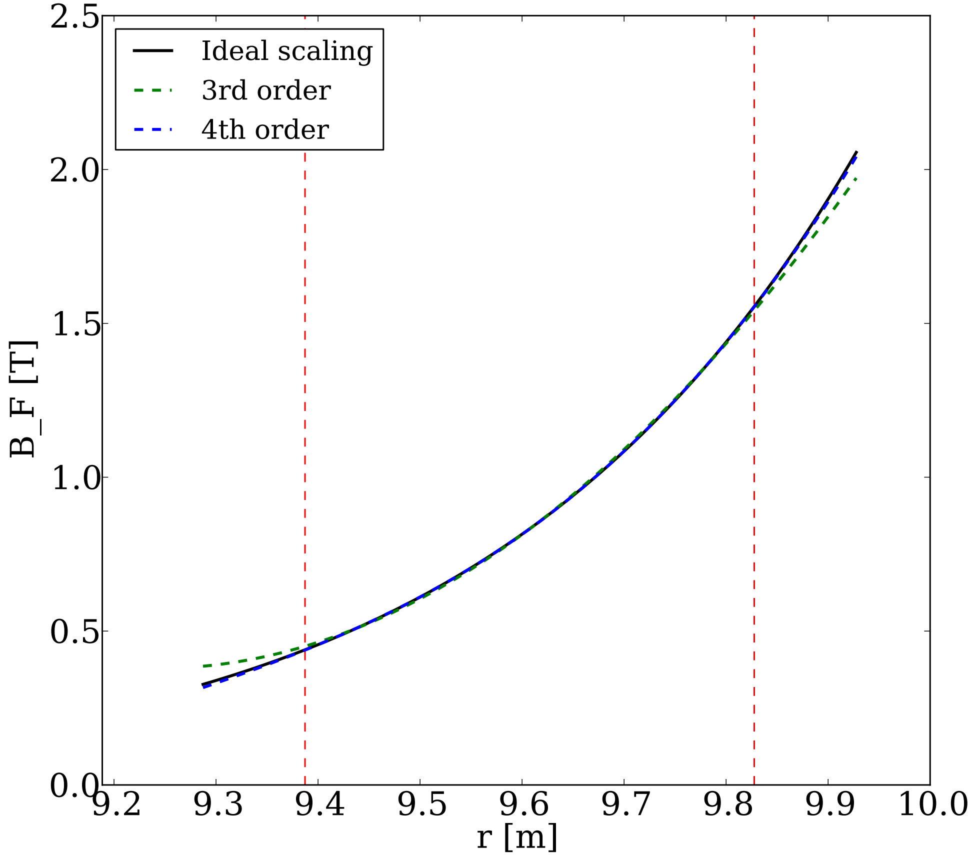
Need to shrink this, perhaps increase D magnet length. More optimisation could be done.



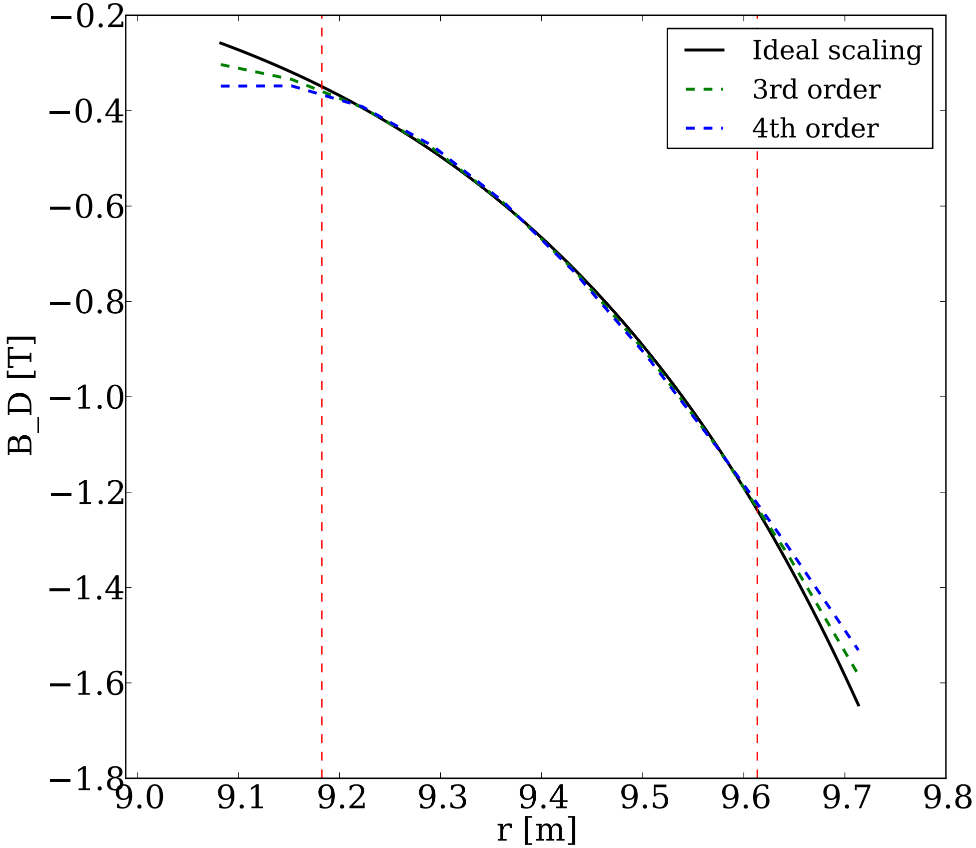


NORMA - Ring

F magnet

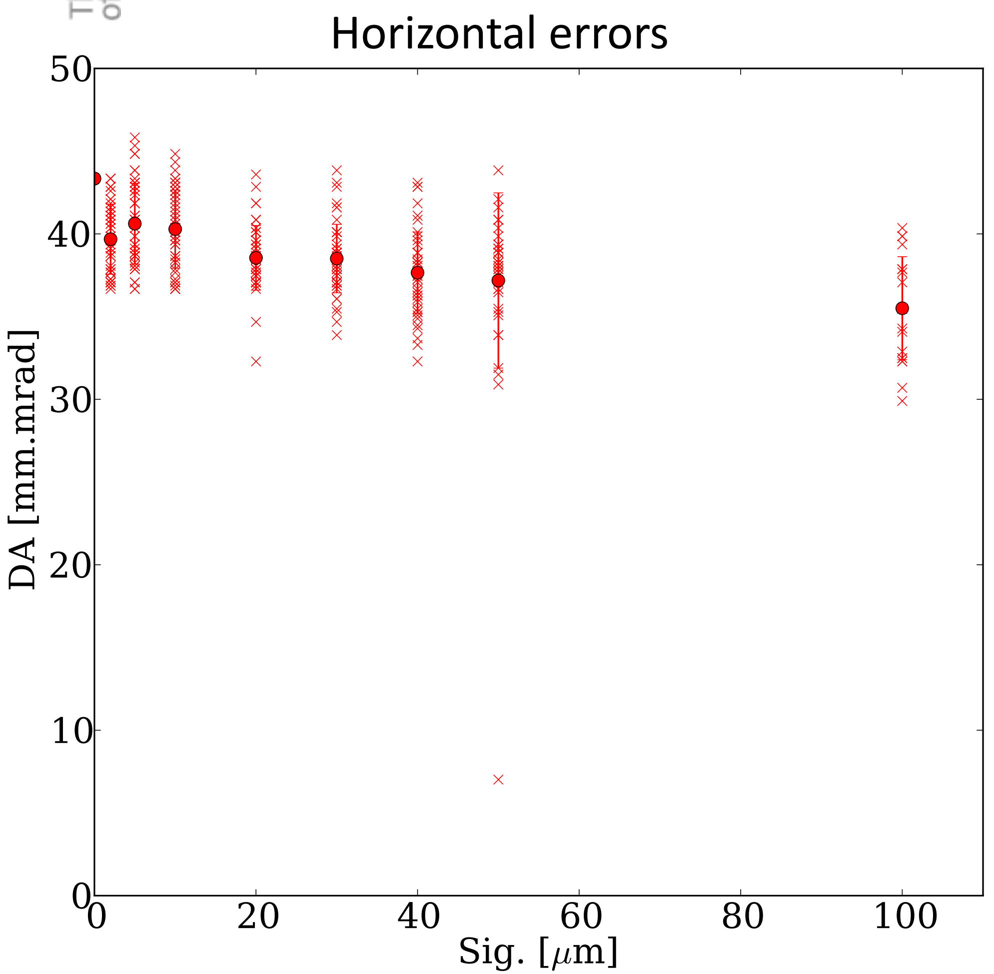


D magnet



Multipole expansion of ideal scaling field.

NORMA - Ring


Horizontal errors
DA [mm.mrad]
Sig. [μm]
0
10
20
30
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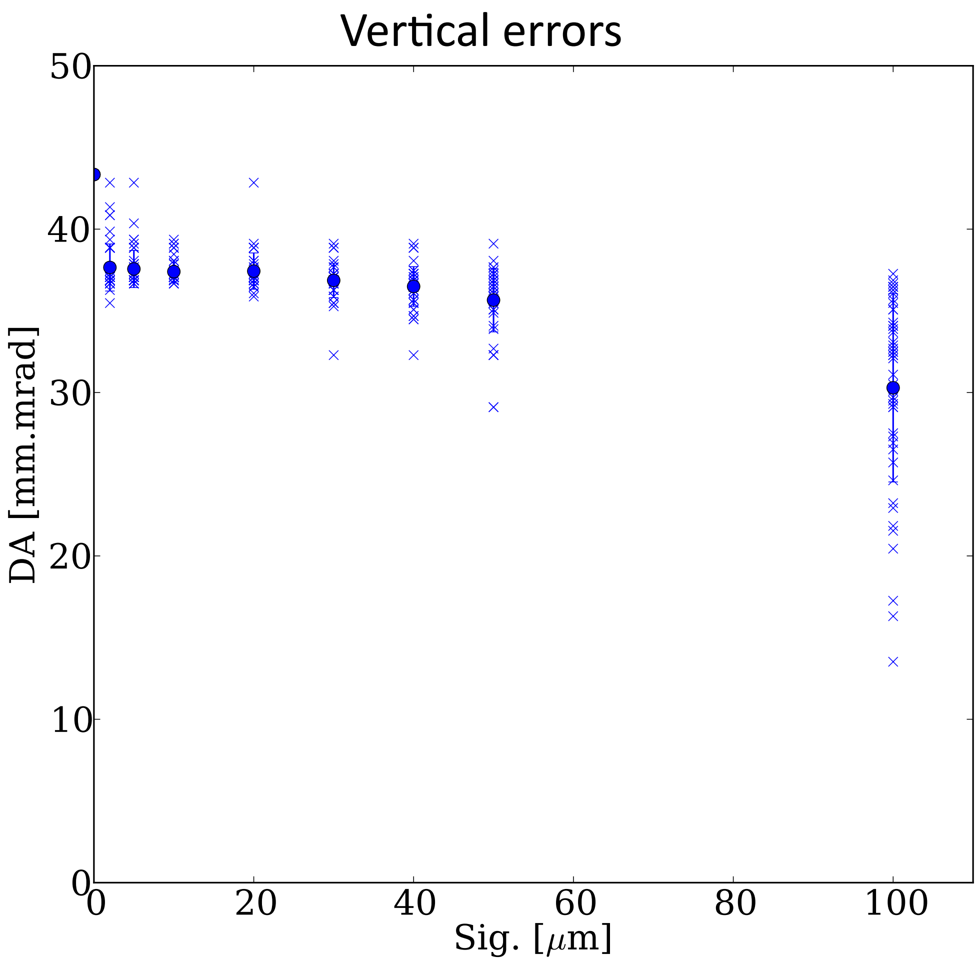
100


Vertical errors
DA [mm.mrad]
Sig. [μm]
0
10
20
30
40
50
0
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40
60
80
100

NORMA - Ring

Comparison of two NORMA rings, 0.65 and 0.6 PF

Parameter [unit]	PF = 0.65	PF = 0.6
Working point (H,V)	8.64, 3.48	6.95, 3.90
Circumference [m]	56.9	61.7
Orbit excursion [m]	0.30	0.44
Field index *k*	37.6	27.6
Max B0 (F,D)	1.68/-1.28	1.77/-1.52
Max DA	21.7	41.8

A word on RF:

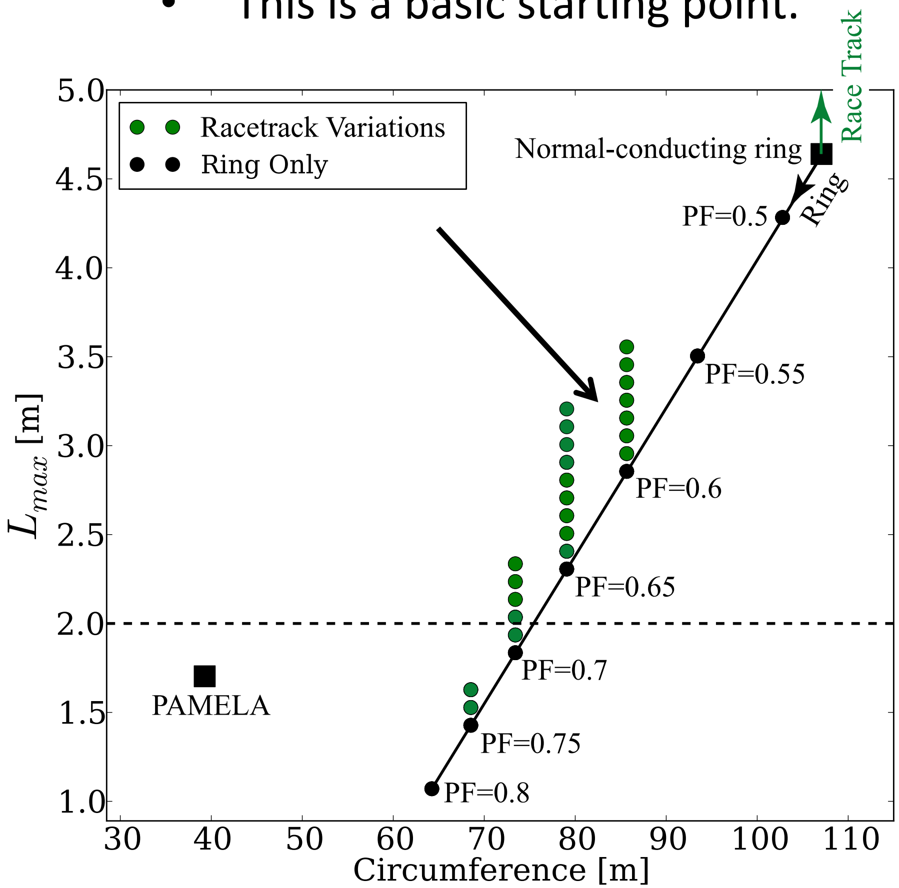
Still there is ~2 m between cells. We need ~300 MeV acceleration and we want to do it in maybe 1500 turns (`similar' to PAMELA) so 0.2 MV per turn.

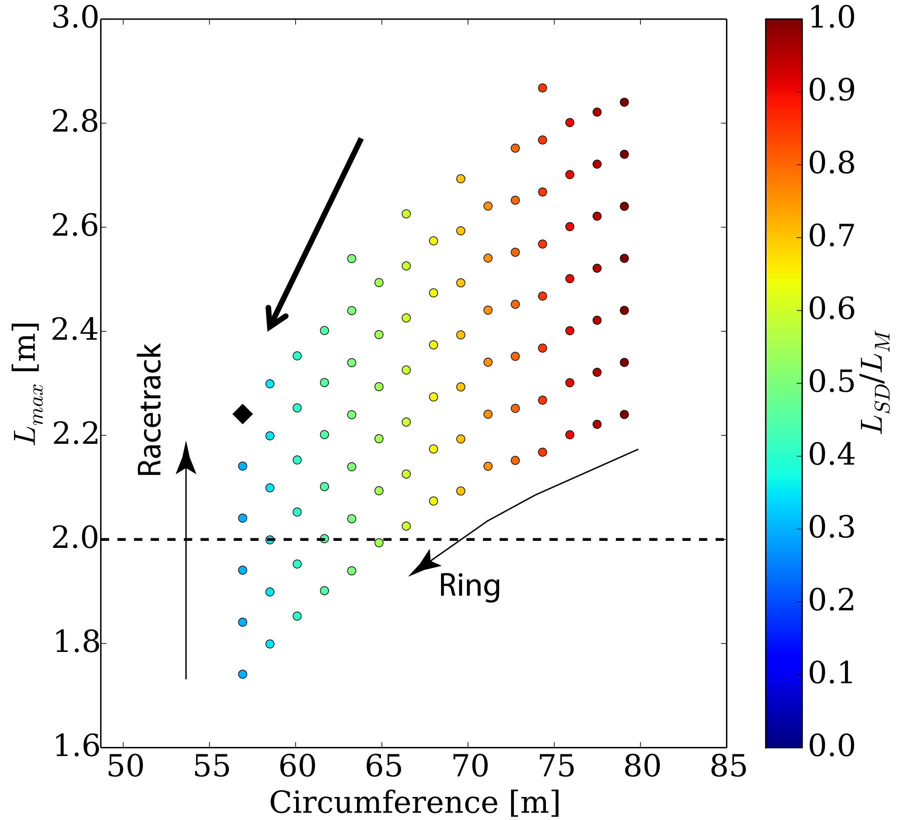
Need sweeping frequency so limit to MV/m in cavities but we have 12 x 2m so probably enough space.

However then we have a potential injection extraction issue. Racetrack will allow is to potentially shrink the arcs but gain space in the straights for everything we need.

NORMA - Racetrack

- Wanted to see what happens when we just break the symmetry – no extra magnets in the straights.
- Stable racetrack geometries were explored where all magnets were of the same family (had the same parameters).
- This is a basic starting point.

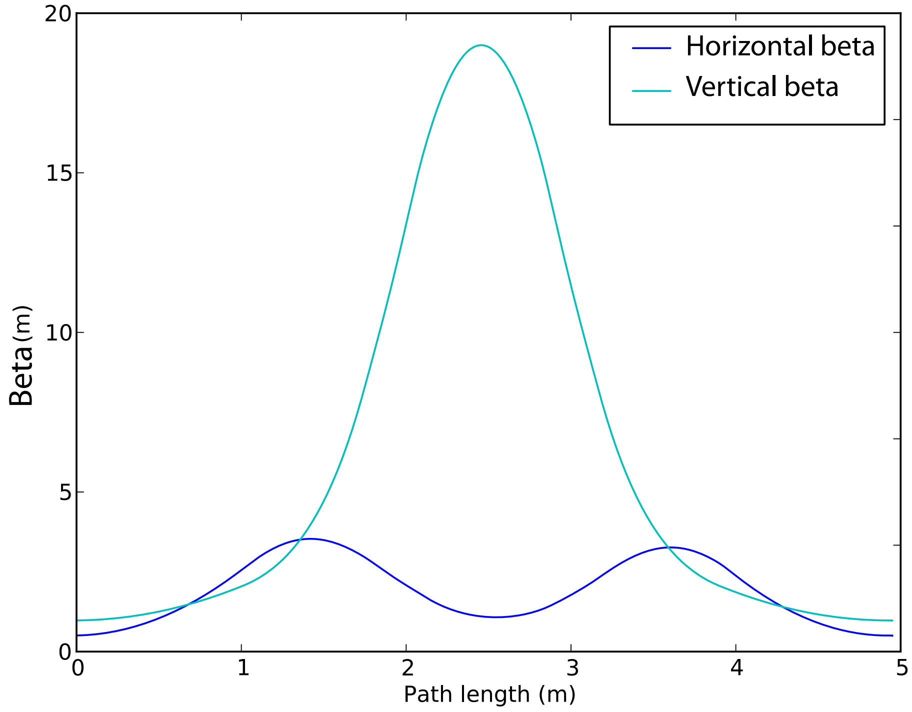




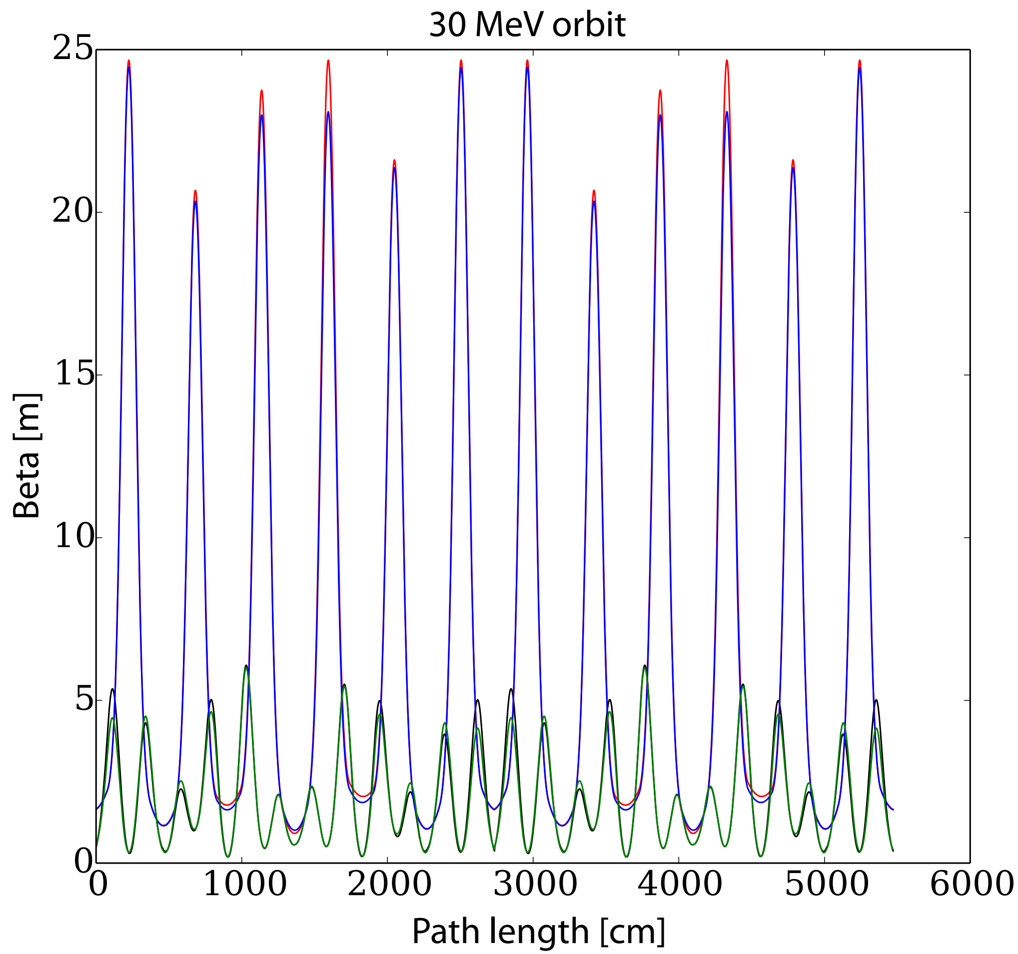
NORMA - Racetrack

- With optimisation of the betafunction in the racetrack in the same way as the ring – we still have an unacceptable DA.

Ring

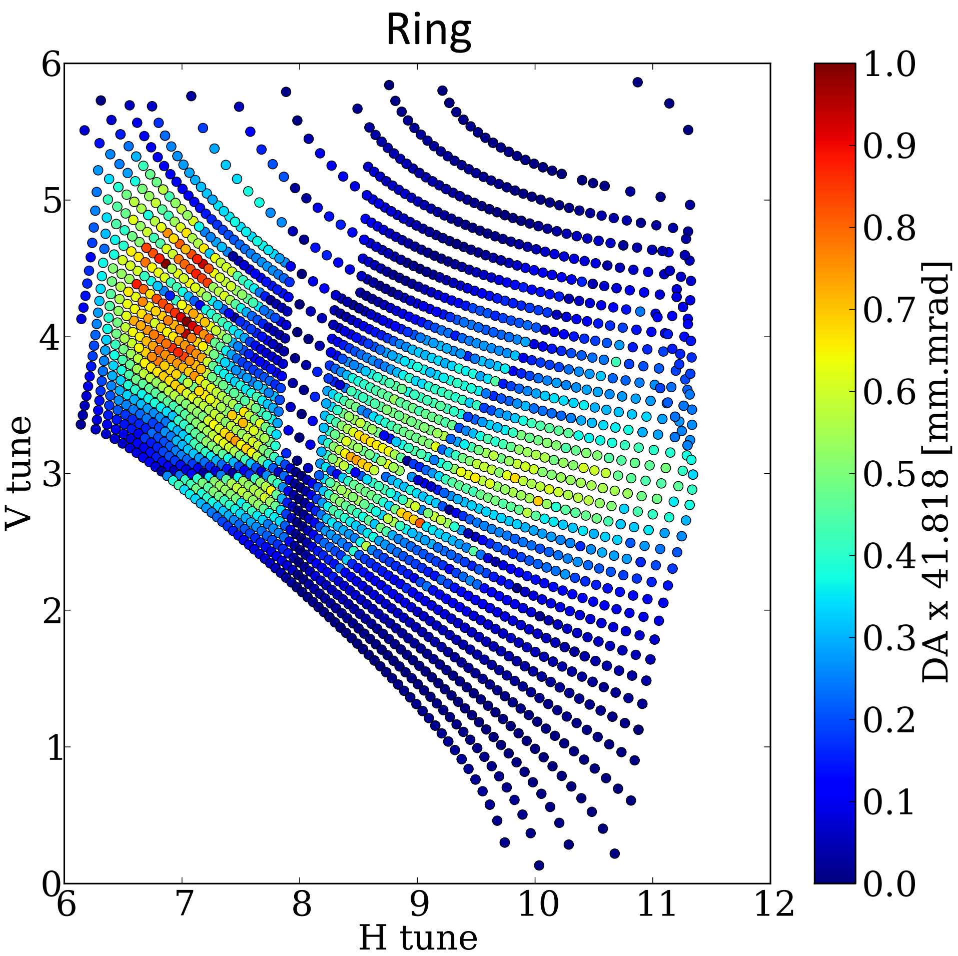


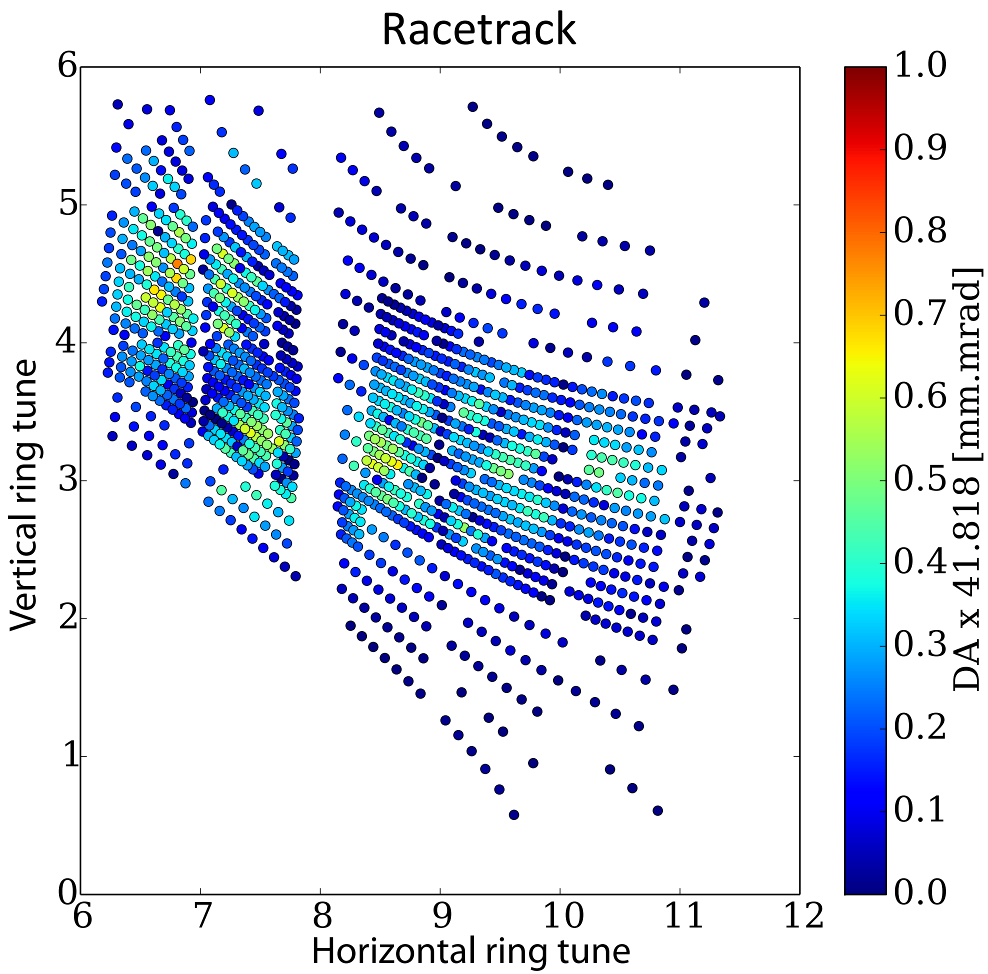
Racetrack



NORMA - Racetrack

- DA too low when symmetry broken and basic racetrack with only 0.1 to 0.5m straight inserted at two locations.
- We could optimise the ring a little more and try to push the DA up in the racetrack with just drifts in the straights.





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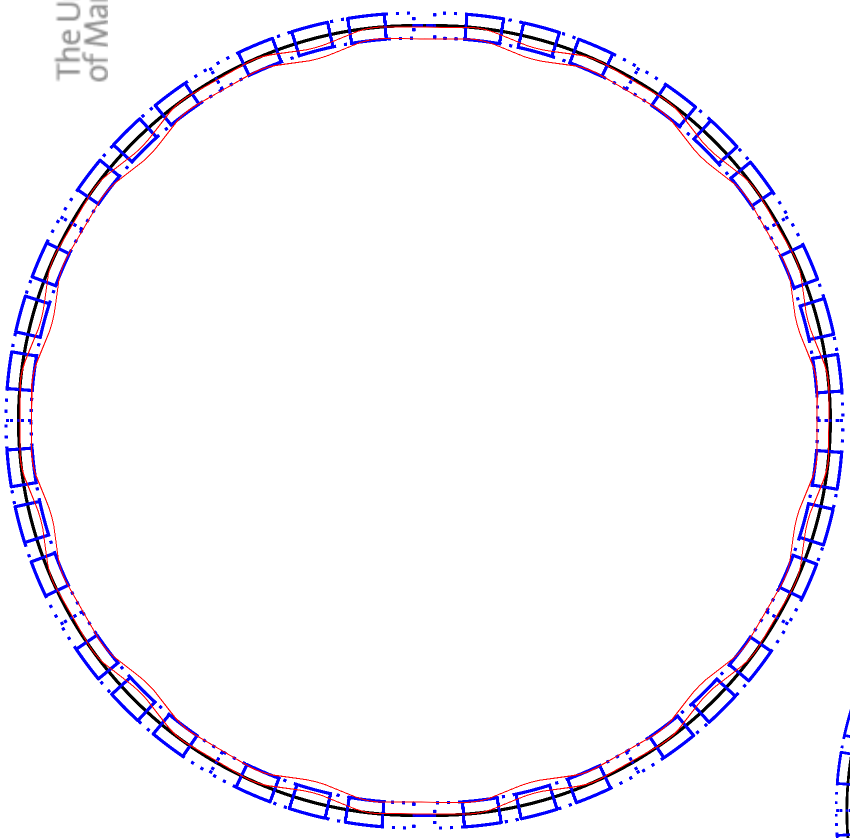
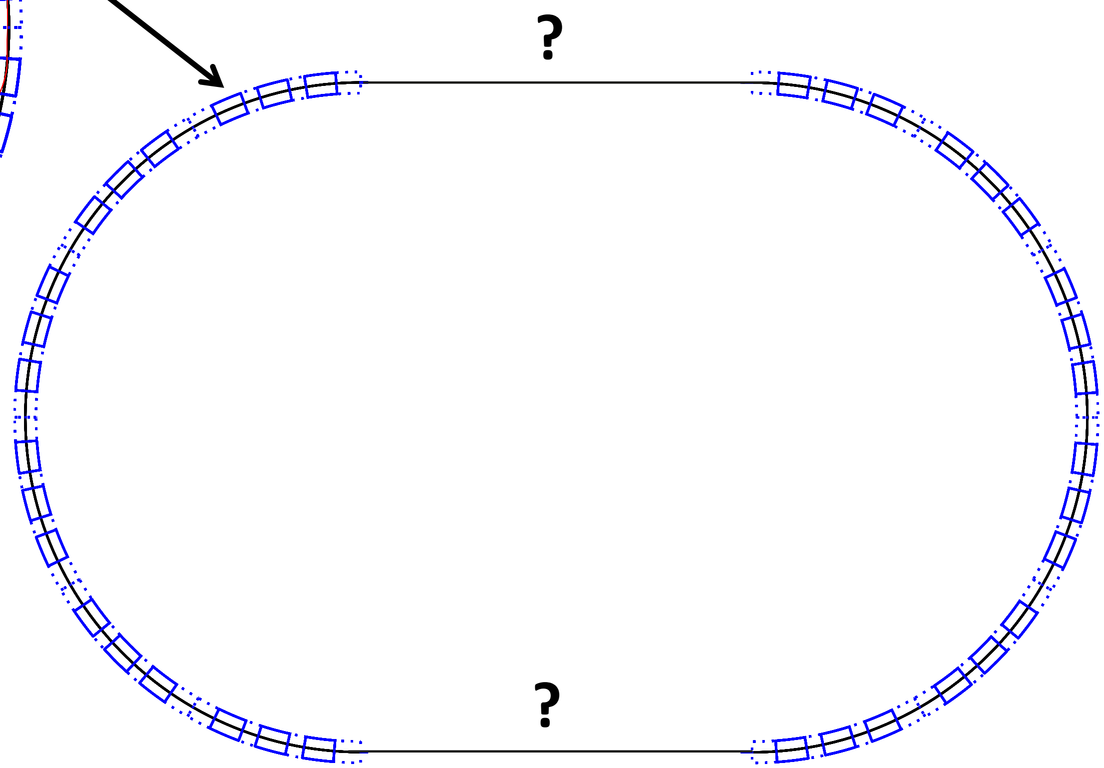
NORMA - Racetrack



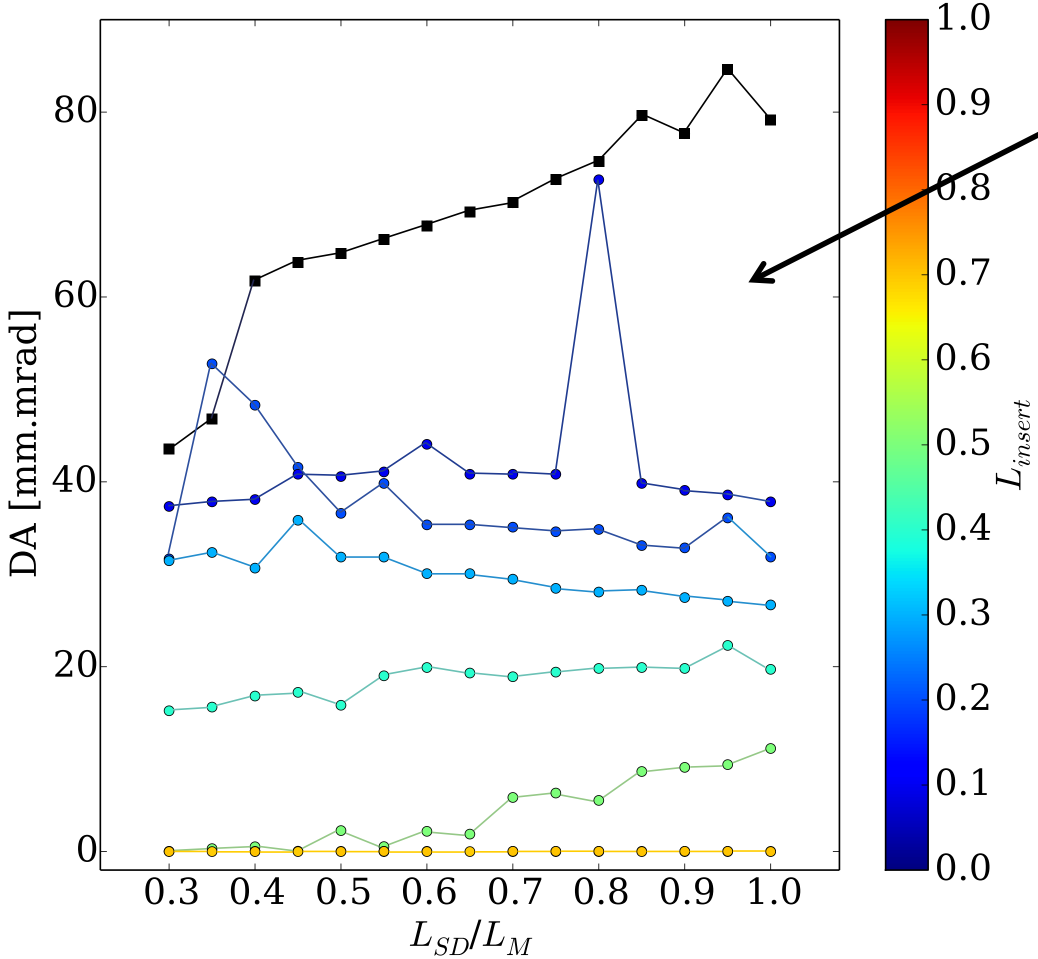
We want longer racetrack straights.
Some matching section and magnets in the straight – for example JB's straight scaling FFAG cell?
Optimise and raise DA in racetrack.



Conclusions and Next Steps

- PyZgoubi routines developed for optimisation of many parameters. Give PyZgoubi a lattice and free parameters and define constraints and let automatic optimisation. Allow automatic calculation of many parameters such as DA in the tune space.
- Developed a preliminary NORMA ring with good enough DA with errors.
- Optimise optics further to bring up ring DA.
- Can we obtain a reasonable DA in a racetrack solution with errors with no matching section or straight section magnets (maybe not)?
- Want to work out what governs the maximum insertable straight and parameterise it – predict max insertable straight given optics parameters.
- Design a matching section and/or straight section optics to generate a good racetrack solution with enough space for RF and injection extraction.

Backup



DA calculated simply by increasing particle action along +ve x-axis in phase space alpha=0.65

DA as a function of real space angle for packing factor 0.7